ARTICLE IN PRESS

Forest Ecology and Management xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Conifer radial growth response to recent seasonal warming and drought from the southwestern USA

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## ARTICLE INFO

*Keywords:*
Dendroclimatology
Conifers
Climate interactions
Southwest USA
Climate change
Forest drought severity index

## ABSTRACT

Future droughts are expected to become more severe and frequent under future climate change scenarios, likely causing widespread tree mortality in the western USA. Coping with an uncertain future requires an understanding of long-term ecosystem responses in areas where prolonged drought is projected to increase. Tree-ring records are ideally suited for this task. We developed 24 tree-ring chronologies from 20 U.S. Forest Service Forest Inventory and Analysis (FIA) plots in the southwestern USA. Climate variables were derived from the PRISM climate dataset (800-m grid cells) to capture the bimodal precipitation regime of winter snow and summer monsoonal rainfall, as well as warm-season vapor-pressure deficit (VPD) and winter minimum temperature. Based on mixed linear models, radial growth from 1948 to 2013 for four conifer species (*Pinus edulis, Juniperus osteosperma, Pinus ponderosa*, and *Picea engelmannii*) responded negatively to warm-season VPD and positively to cold-season precipitation. *Pinus* spp. benefited from warm-season precipitation linked to the North American monsoon, and *Pinus* spp. and *J. osteosperma* radial growth increased with warmer cold-season minimum temperature. However, warmer cold-season minimum temperatures countered the beneficial influence of cold-season precipitation for radial growth in *Pinus* spp. and *J. osteosperma*, while *P. engelmannii* was unaffected. Also, enhanced drying effects of warm-season VPD associated with decreased cold-season precipitation negatively affected radial growth of *Pinus* spp. and *P. engelmannii*. Of the four conifer species studied, *Pinus* spp. are most affected by droughts since 1948, while *P. engelmannii* and *J. osteosperma* appear to be more resilient. Investigating seasonal climate responses and interaction effects on radial growth in areas impacted by severe drought helps identify species that may be particularly at risk from climate change impacts in the Anthropocene.

## 1. Introduction

Drought negatively impacts tree species and is projected to become more frequent in many regions, including the southwestern USA ("Southwest"), under future climate scenarios (Stocker et al., 2014). Conifer species have experienced landscape-wide drought-related mortality events over the last few decades (van Mantgem et al., 2009; Allen et al., 2010), especially during the early millennial drought peaking in 2002 (Breshears et al., 2005; Shaw et al., 2005). However, some tree species and forests are more drought-resilient than others (McDowell et al., 2008), and can possibly lead to repopulation of drought-stricken areas.

Inter- and intra-annual trends in seasonal climate contribute to the overall health and response of forests after severe drought. For instance, high precipitation in the Southwest during 1978–1995 allowed for rapid radial growth, making trees more susceptible to mortality through beetle infestation and associated pathogens during the drought years that followed (Breshears et al., 2005; Swetnam & Betancourt 1998). Across the extra-tropical Northern Hemisphere, years with anomalous climatic water deficit, a measurement of drought stress first proposed by Stephenson (1990), cause drought legacy effects in radial growth for a few years to follow (Anderegg et al., 2015).

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https://doi.org/10.1016/j.foreco.2018.01.044
Received 26 August 2017; Received in revised form 18 January 2018; Accepted 25 January 2018

Please cite this article as: Truettner, C., Forest Ecology and Management (2018), https://doi.org/10.1016/j.foreco.2018.01.044

In the Southwest, the major drivers of annual radial growth of conifers from a range of elevations are warm-season vapor pressure deficit (VPD) and cold-season precipitation (Williams et al., 2013), with deficits of cold-season precipitation typically defining drought conditions. Moreover, climatic conditions prior to droughts affect resistance and recovery of radial growth during post-drought years (Peltier et al., 2016). These relationships are derived largely from tree ring records from the early 20th century, with the number of records decreasing sharply for the past few decades (Williams et al., 2013). Refining understanding of how climate drives forest response in more recent years is vital, especially considering the projected increase of temperature and aridity in the Southwest (Seager et al., 2007; Udall & Overpeck, 2017).

Much of the Southwest is defined by a bimodal precipitation regime with peaks during both the cold- and warm-season, the latter due to the North American monsoon (Douglas et al., 1993; Higgins et al., 1999; Vera et al., 2006). Dry periods with warm temperatures and high VPD are particularly acute in late spring prior to the initiation of the monsoon and again in early fall after the monsoon and before cold-season precipitation (Williams et al., 2013). A climate variable often overlooked when investigating drought in this region is cold-season minimum temperature, which plays a major role on snowpack duration, stream runoff, and snow-to-rain transition (Knowles et al., 2006; Pederson et al., 2013). A rise in cold-season temperatures can increase snowmelt in early spring leading to enhanced drought stress on vegetation during the summer and to higher frequency of wildfires in forests of the western USA (Westerling et al., 2006). Increased cold-season temperatures could also lead to a quicker snow-to-rain transition as 21st century abrupt climate change continues. Thus, cold-season minimum temperature is an important variable to consider in relation to cold-season precipitation when evaluating radial growth responses to climatic variability across elevations and latitudes.

The objective of our study was to understand recent drought impacts on dominant conifer species, with a focus on radial growth during the instrumental monitoring period starting in 1948. More specifically, our main goal was to test if and to what extent seasonal (e.g. warm- versus cold-season) climate variables and their interactions affected annual radial growth in relation to the bimodal precipitation regime of the Southwest. We addressed these goals by collecting tree cores from 20 sites for four conifer species across the Southwest. Site chronologies were developed from ring-width records to provide indices of annual radial growth, which we analyzed in the context of their climatic drivers.

## 2. Materials and methods

Conifer tree species dominate the mid-to-upper elevation landscapes in the spatially heterogeneous Southwest (i.e., Arizona, New Mexico, Colorado, and Utah). Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) is most abundant near the upper treeline, ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) dominates the mid-elevations, and two-needled pinyon pine (*Pinus edulis* Engelm.) coexists with Utah juniper (*Juniperus osteosperma* (Torr.) Little) at the lower end of the conifer range (Vankat, 2013).

### 2.1. Tree-Ring sampling and laboratory analysis

We sampled 20 U.S. Forest Service Forest and Inventory Analysis (FIA; Gillespie, 1999; Shaw, 2017) plot locations in summer 2014 throughout the states of Arizona, New Mexico, Utah, and Colorado (Fig. 1). These plots were selected from a set of 120 candidates from the FIA database using the following criteria: (1) the stand type was classified by FIA during a previous plot visit as pinyon/juniper woodland, ponderosa pine, Engelmann spruce, or Engelmann spruce/subalpine fir (i.e., stands dominated by one of the focal species), (2) the plot was scheduled for re-measurement by FIA during the 2014 field season (i.e., previously measured in 2004, except in the case of New Mexico plots which were last measured in 1999), and (3) located on public land. The candidate plots were further screened using recent aerial photography to eliminate plots that were disturbed by fire or harvesting activities since the last plot visit, and to identify plots that were within 1 km of accessible roads. The final sample of 20 was intended to cover the full range of latitude and elevation, and therefore climatic variation, on sites occupied by the target forest types within the area of interest.

Ten trees per species representing a range of sizes were selected within or near ($< 5$ m horizontal distance) each FIA plot. After measuring stem diameter at breast height ($\sim 1.4$ m), two tree cores were extracted with an increment borer on opposite sides of the main stem in a direction parallel to the slope contours. In the laboratory, tree cores were mounted, sanded, and visually cross-dated (Stokes & Smiley, 1968) with the assistance of nearby tree-ring chronologies from the International Tree-Ring Data Bank (Grissino-Mayer & Fritts, 1997). Tree cores were then scanned and each ring was measured to the nearest 0.001 mm with the WINDENDRO2012 measurement system. Ring-width series were quality controlled using the COFECHA software (Grissino-Mayer, 2001). All tree-ring chronologies were based on a minimum of ten cores dating back to 1948, and sixteen cores as the maximum. Tree cores were measured back to 1940 unless the tree was younger than 66 years.

Raw ring-width measurements were first detrended by fitting a cubic smoothing spline with a 50% frequency response for a 40-year period (Cook and Peters, 1981) to standardize age-growth trends among FIA plots. We further “pre-whitened” the detrended ring-width series to remove time-series auto-correlation (Biondi and Swetnam 1987) using the auto-regressive model in the dendrochronology program library (dplR) that is part of the R software environment (Bunn et al., 2014). The arithmetic mean of annual ring width indices was calculated for each species to build plot-level, species-specific tree-ring chronologies. Empirical measures including expressed population signal, Gini coefficient, and 1st-order autocorrelation were used to quantify the strength of dendroclimatic signals (Wigley et al., 1984; Biondi & Qeadan, 2008; Box & Jenkins, 1976).

### 2.2. Seasonal climate variables

We calculated seasonal climate variables using monthly climate data from the Parameter-Regression at Independent-Slopes Model (PRISM) dataset with 800-m spatial grid cells (Daly et al., 2008). Cold-season precipitation was defined by mean monthly precipitation from previous November to current March, which is consistent with previous studies (Williams et al., 2013). July-September precipitation has been used to define the temporal range of monsoon precipitation (Romme et al., 2009), and thus, we used mean monthly precipitation for the July-September period to quantify warm-season precipitation.

To investigate the interaction of seasonally derived temperature variables with the bimodal precipitation regime, we calculated warm-season VPD and cold-season minimum temperature. Warm-season VPD was given by the mean monthly VPD of six months, antecedent VPD conditions for three months from the previous year of annual radial growth (August-October) and three months from the current year (May-July) (Williams et al., 2013). Cold-season minimum temperature was defined by mean monthly minimum temperature from the previous November to the current March. We additionally considered growth-season maximum temperature (April-October mean maximum monthly temperature), antecedent VPD (previous August-October), and current VPD (May-July) as independent variables, which were highly correlated with warm-season VPD. Pearson’s linear correlation coefficient was calculated between each tree-ring chronology and seasonal climate variable to investigate site-specific radial growth response to seasonal climate variables.